2020 DOE VEHICLE TECHNOLOGIES ANNUAL MERIT REVIEW

JUNE 2020

ENERGY-EFFICIENT CONNECTED AND AUTOMATED VEHICLES – EEMS016

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Project Overview

Timeline

- Project start: Oct. 2016
- Project end: Sep. 2019
- Percent complete: 100%

Budget

- Total Funding (3 years): $2.3M
- FY19 Funding: $850,000
- FY20 Funding: $0

Partners

- Argonne: lead
- LLNL, LBNL: test data

Barriers

- Development of Connected and Automated Vehicles (CAVs) not driven by energy-efficiency
- Eco-driving research rarely integrates **advanced powertrain technologies**
- Combining dynamics and powertrain control results in **complex control problems**
- **Real-world implementation** often challenging
- Many **exogenous factors** (e.g. traffic), affect energy saving potential of eco-driving
- **Lack of practical tools** for “powertrain-aware” eco-driving algorithm development

Objectives and Relevance

#1: CAV Eco-Driving Control

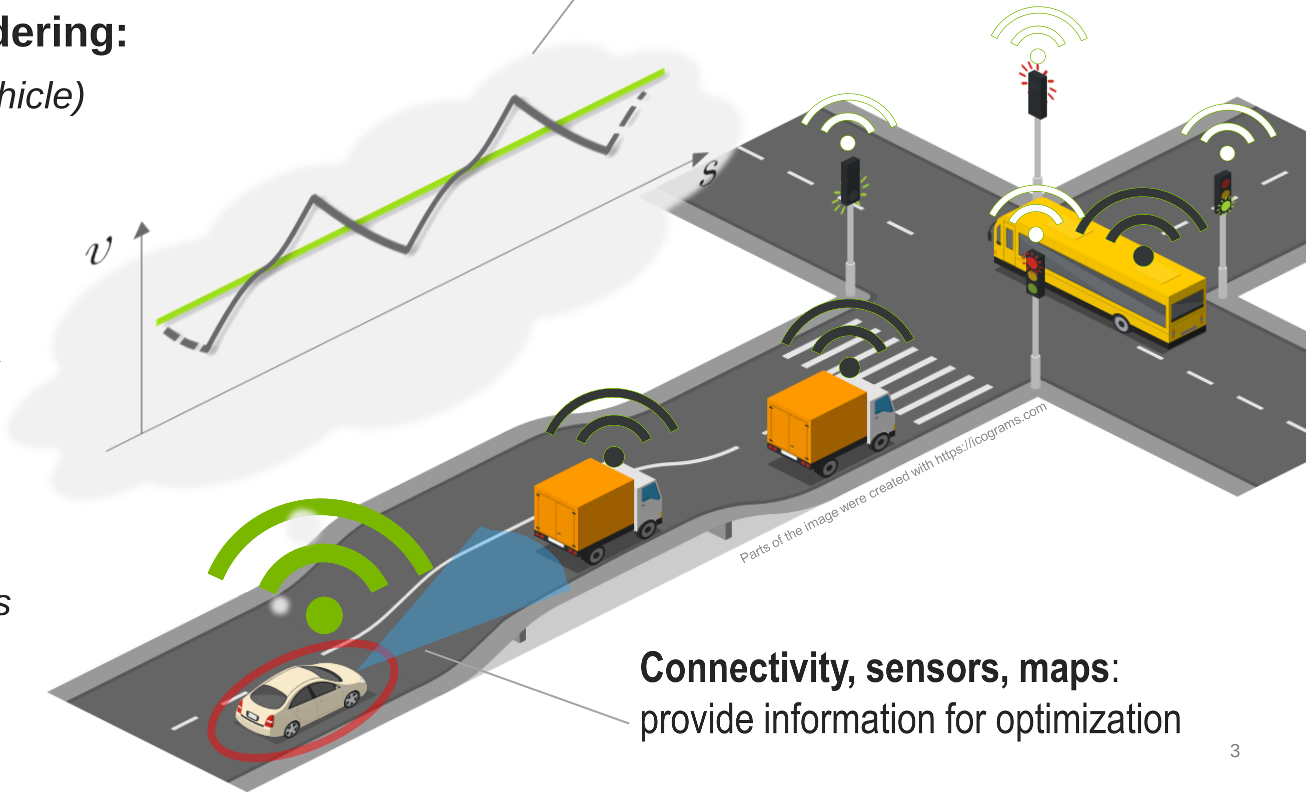
Minimize Fuel/Energy considering:

- *Immediate traffic (preceding vehicle)*
- *Traffic regulations*
  - *Speed limits*
  - *Traffic lights*
  - *Stop signs*
- *Road condition (grade)*
- *Powertrain type and operations*

Requirements:

- *Real-world implementable*
- *Able to work for entire missions*

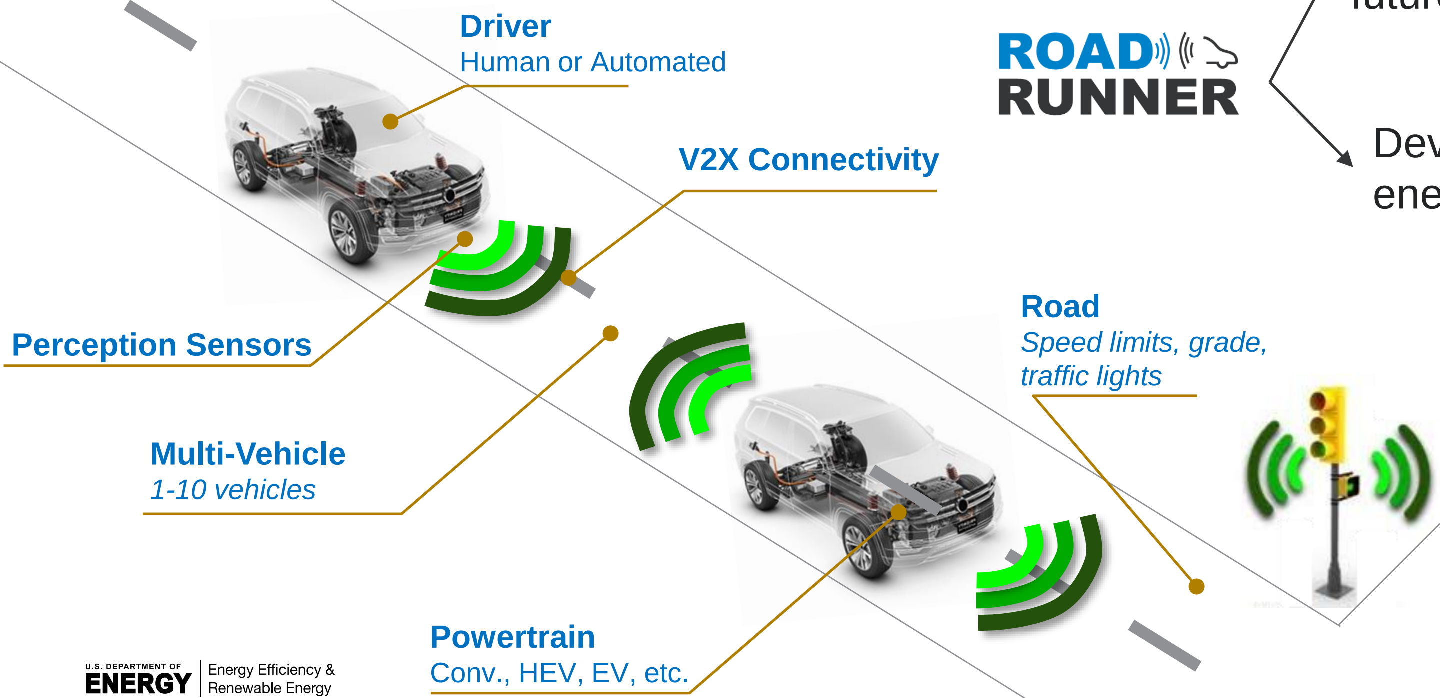
Automation: enables control of vehicle speed



Connectivity, sensors, maps: provide information for optimization

Objectives and Relevance

#2: CAV Simulation Framework



ROAD RUNNER

Energy impact of current and future CAV technologies

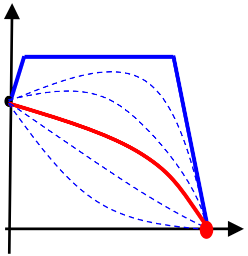
Development of CAV for energy-efficiency

Approach

CAV Eco-Driving: Control of Powertrain AND Longitudinal Speed

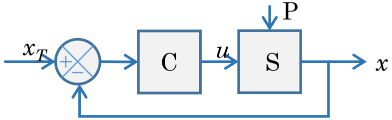
A. Optimization & Trajectory planning

- *Future horizon >> most energy-efficient state & control trajectory (speed, torque, SOC, etc.)*
- *Optimal control, Quadratic programming, etc.*



B. Real-Time Control

- *Current state >> what command to follow optimal state & ctrl. trajectory?*
- *MPC, Feedback loops, transients, dynamics*



Driving Scenarios

Powertrains

ROAD RUNNER

Energy Impacts

Real-World Data

Chassis Dyno
Track
On-road

CAV Modeling and Validation

Platooning, ACC, Human Driving

Milestones

Eco-driving: Demonstrate a "real-world implementable" controller working online in RoadRunner environment
✓ ***Complete***

2019 Q1

2019 Q2

2019 Q3

2019 Q4

Quantify energy impact of advanced optimal eco-driving over a range of representative scenarios
✓ ***Complete***

RoadRunner: Complete the development and validation of human and automated driver models.
✓ ***Complete***

ACCOMPLISHMENTS

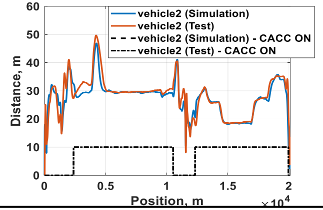
RoadRunner: Simulation Tool for Energy-Efficient CAV Control Development

Validated Several Models for RoadRunner

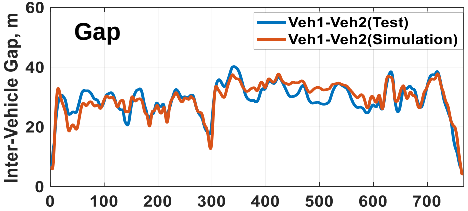
ROAD RUNNER

Simulation of Powertrain and Driving Dynamics for CAV

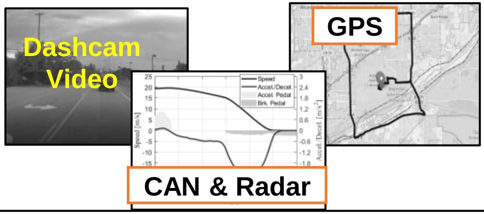
Truck Platooning

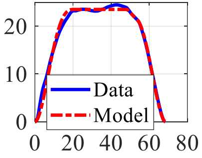


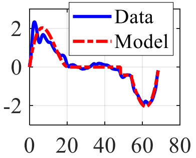
Prius Prime ACC



Human Driver







ACCOMPLISHMENTS

Energy-Efficient CAV Control Development

Various Types of Control Optimization

<table>
<tr><th colspan="2">Optimization</th><th>Speed-only</th><th colspan="3">Speed + Powertrain</th></tr>
<tr><td colspan="2">Powertrain type</td><td>Any</td><td>EV</td><td>ICEV</td><td>HEV</td></tr>
<tr><td colspan="2" rowspan="3">Control variables</td><td rowspan="3">Acceleration</td><td rowspan="2">Motor torque</td><td>Engine torque</td><td>Motor & engine torques</td></tr>
<tr><td colspan="2">Gear shifting</td></tr>
<tr><td colspan="3">Brake force</td></tr>
<tr><td colspan="2">Cost function to minimize</td><td>Acceleration “energy”</td><td>Battery energy</td><td>Fuel mass</td><td>Equivalent energy consumption</td></tr>
<tr><td rowspan="3">Subject to</td><td>System dynamics</td><td>Vehicle dynamics</td><td colspan="3">Vehicle dynamics including powertrain operation</td></tr>
<tr><td>State constraints</td><td colspan="4">Speed limits and preceding vehicle</td></tr>
<tr><td>Interior-point constraints</td><td colspan="4">Traffic signal phase and timing (SPaT) [when V2I enabled]</td></tr>
<tr><td colspan="2">Boundary conditions</td><td colspan="4">Final position and final speed given initial position and speed</td></tr>
<tr><td rowspan="2">Implementability</td><td>Execution speed</td><td colspan="4">Faster … Slower</td></tr>
<tr><td>Robustness and adaptation for implementation</td><td>Very robust and no need to adapt to vehicle type</td><td colspan="3">• Speed + Powertrain optimization needs adaptation (new code generation) according to the type of powertrain
• Requires more calibration (e.g. trade-off drivability and efficiency)</td></tr>
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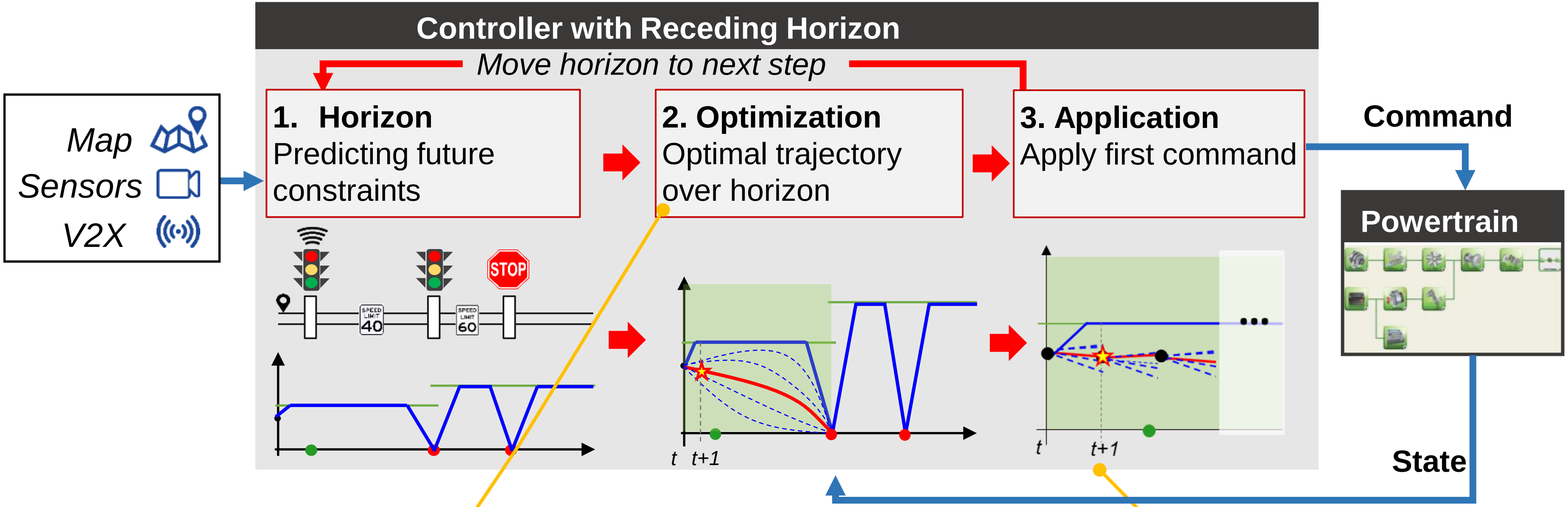
Receding Horizon Enables Real-Time Implementation with Control Feedback



Optimization algorithms (solvers)

- Speed-only
- Speed + Powertrain

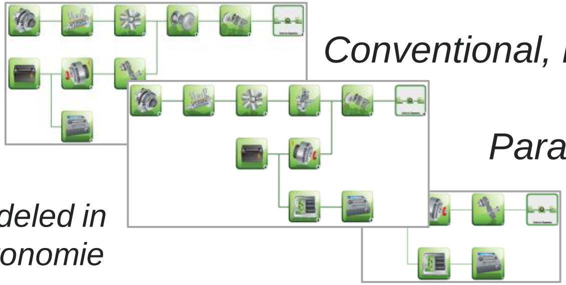
Feedback loop allows real-time implementation:

- Optimization model is simplified
- Knowledge of environment is imperfect
- Future speed of preceding vehicle unknown

Large Case Study with Real Routes to Quantify Benefits of CAV Controls

Vehicles

Midsize, Current & 2025 Tech.



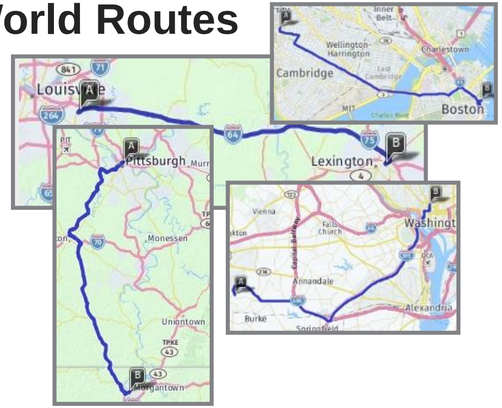
Conventional, ICE

Parallel HEV

BEV 200

Modeled in Autonomie

Real-World Routes



Data from HERE maps
9 Suburban
9 Urban
16 Highway
10 Mixed

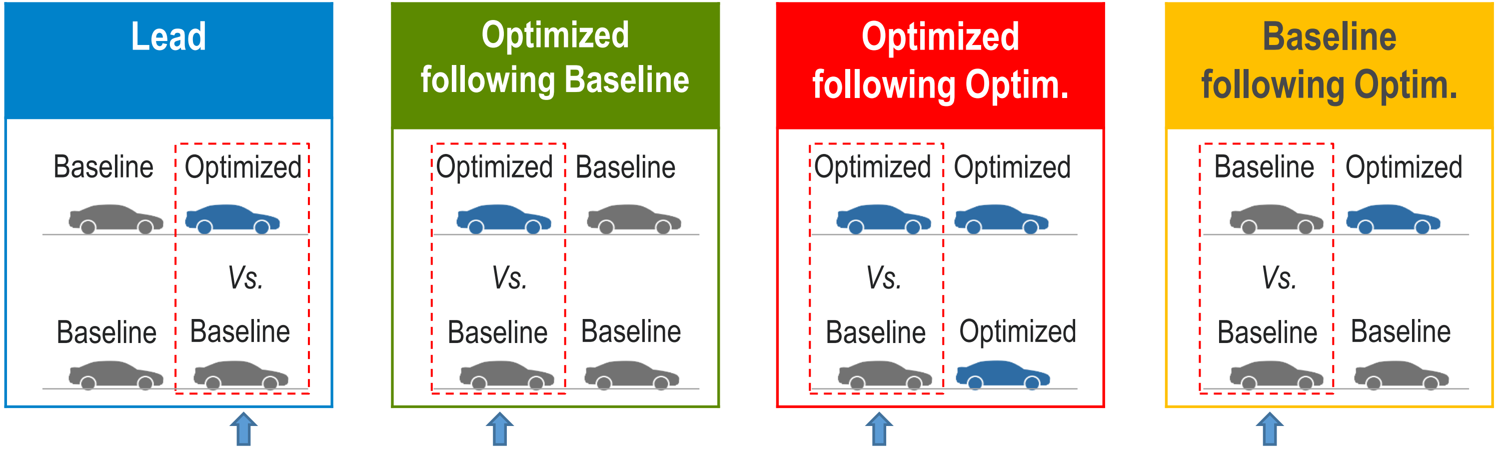
Scenarios

- *2 vehicles, no preceding traffic*
- *Traffic signal phase and timing info (V2I): 0% or 100%*
- *CAV penetration: 0%, 50%, 100%*

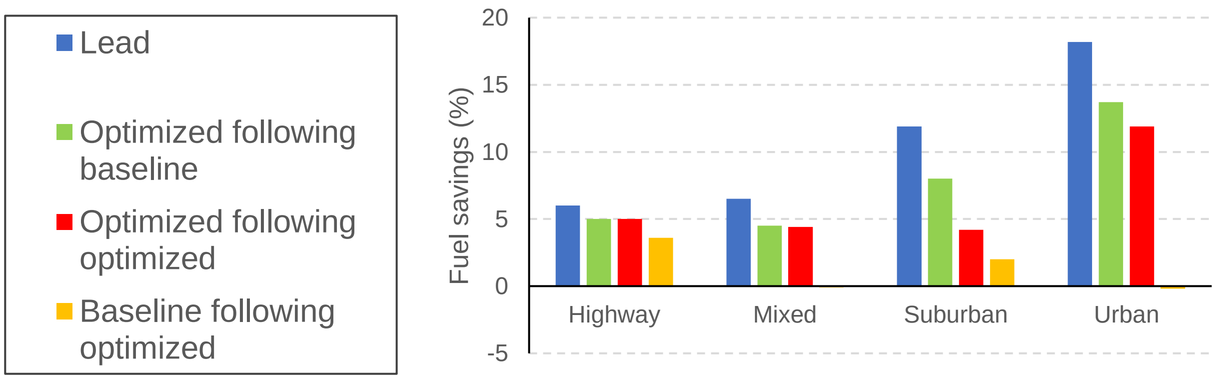
Control

Control	Description
Baseline	Baseline w/o V2I = no optimization ~ Human driver Baseline w/ V2I = no optim. + eco-approach (EA) ~ ACC+EA
EcoDrv Spd/Accel	Eco-driving with Speed/Acceleration Optimization
EcoDrv PT+Spd	Eco-driving with Powertrain and Speed Optimization

Impact of Scenario/Position

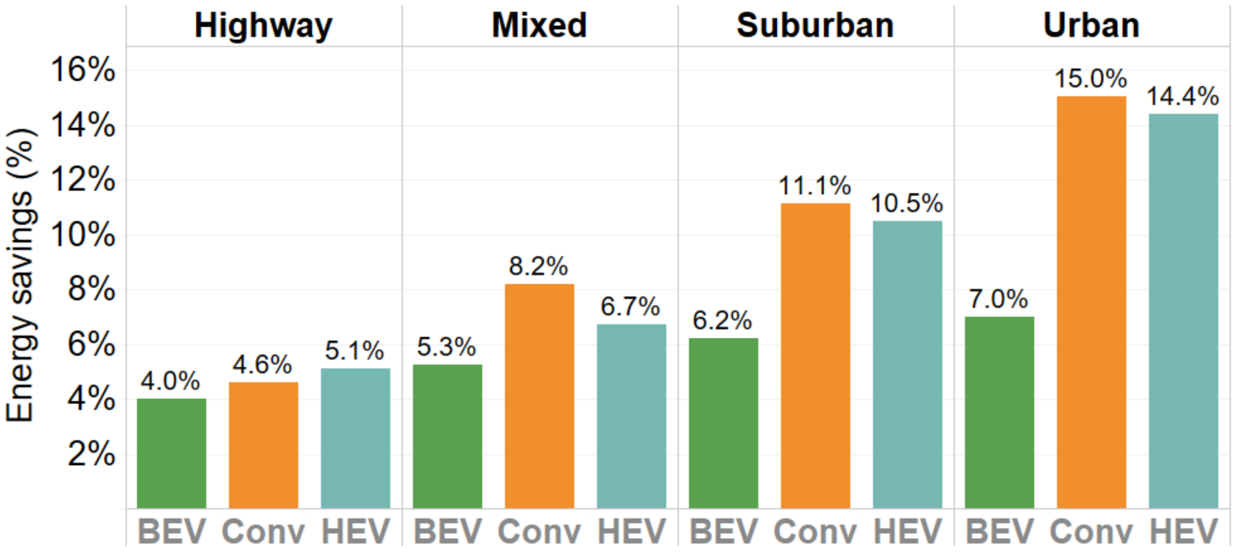


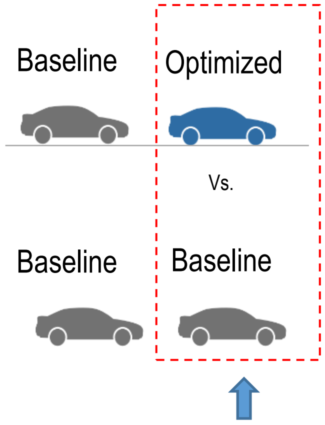
<u>Assumptions:</u>
HEV, current tech.
Speed+PT control
No V2I



- *Greater benefits for lead vehicle*
- *Non-equipped vehicles could benefit too*

Impact of Powertrain Type

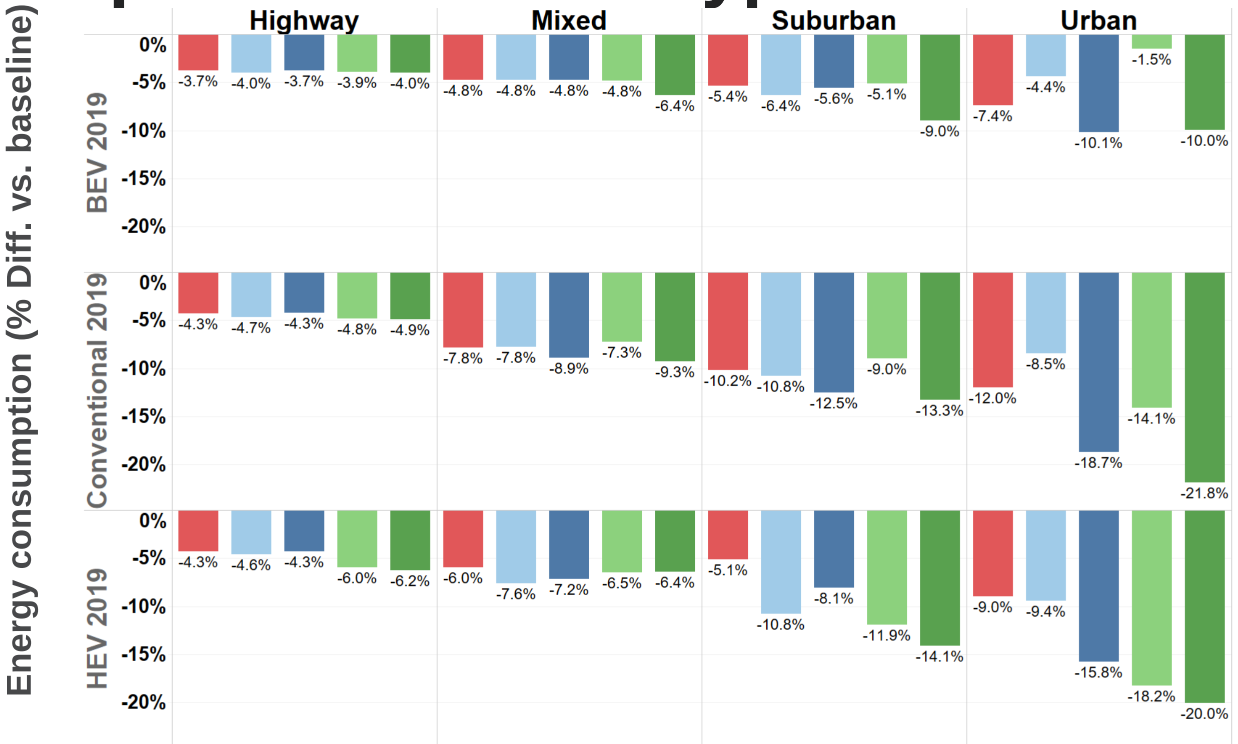


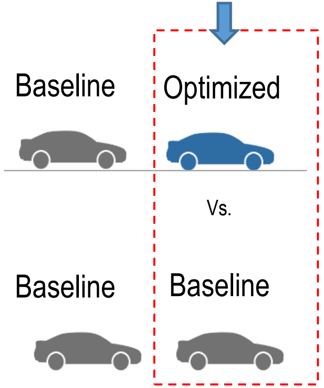


- *Greatest savings achieved on urban roads*
- *Greatest potential for conventional and HEV*

Current tech.,
***average** for all controllers,*
w/ or w/o V2I

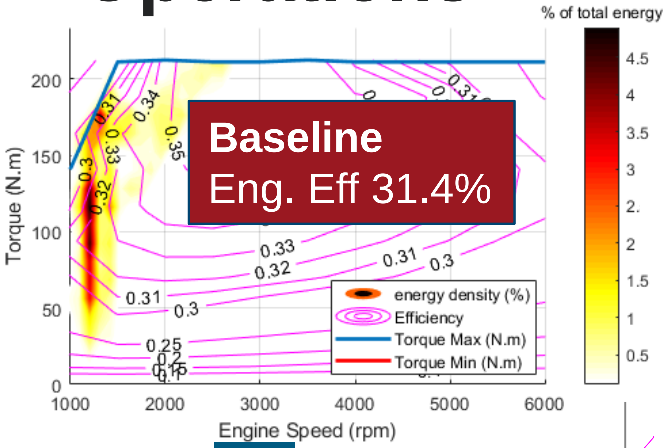
Impact of Control Types and V2I



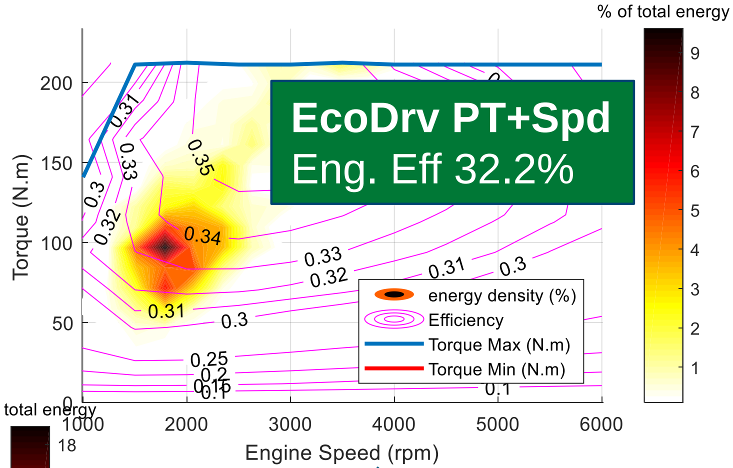


- *Adding powertrain optimization or V2I generally leads to greater savings*
- *Consistency in results over large number of scenarios is challenging, due to imperfect calibration, partial future horizon knowledge, simplified models for optimization, etc.*

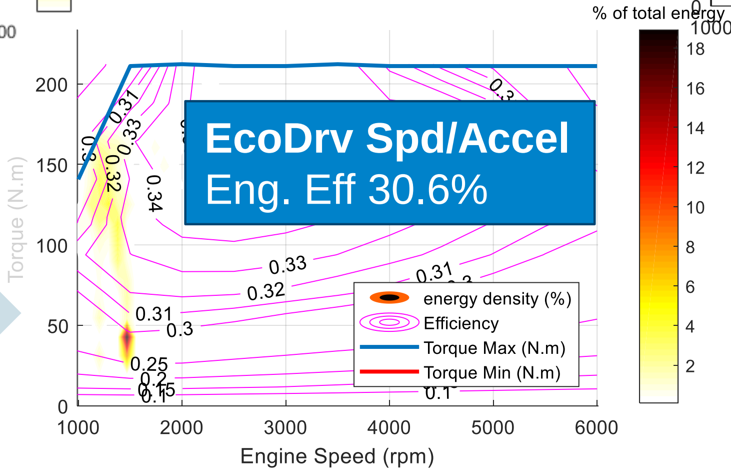
Eco-Driving Impacts Component Operations



Urban road scenario
HEV, current technology, lead position



Eco-driving reduces accelerations and overall road load, reducing engine efficiency



Adding powertrain to the optimization shifts engine operations to higher efficiency areas

CLOSING REMARKS

Response to Previous Year Reviewers' Comments

Reviewer comments	Response
The modeling approaches developed provided excellent tools for the research team to conduct the research work proposed.	We are working on making these tools available to industry and research community
The reviewer suggested three areas of improvement: further human driver-behavior classification, statistical sufficiency (for determining energy impact), and the consideration of travel time as part of the optimization problem.	All three will be addressed in future work, provided funding (project ended in Sep. 2019).
It was unclear to the reviewer whether the human driver used to validate the baseline simulations was a professional driver or representative of on-road driving behavior in the United States	Data used for validation was limited. New datasets are being incorporated into the research, including driving data from OEM fleet drivers (not professional drivers), as well as from customer data (e.g. EEMS086).
The lack of a baseline lead- optimized follow vehicle scenario is a significant oversight, according to the reviewer, given the intent to claim energy savings when the vehicles are in the opposite order.	All combinations of optimized/non-optimized positions were simulated: Lead (L) Optimized (O)/ Following (F) Non-Optimized (N) [LO/FN]; LO/FO; LN/FO; LN/FN
It was not clear to the reviewer what information about the routes, if any, was pulled from HERE Technologies, other than segment length and intersections.	Segment length, speed limit, intersection type, grade; traffic speed and curvature also pulled, but not used yet – integration of traffic and road curvature is part of future work (provided funding)
The reviewer commented that no information was provided in the design for forward work for FY 2019 on how traffic volume or lateral vehicular movements are to be addressed	Integration of traffic is subject to future funding. The plan is to insert a lead vehicle that serves as a proxy for traffic conditions; this would use a stochastic data-driven model (SVTRIP), coupled with traffic condition information (from HERE maps).

Partnerships and Collaborations

Data for model validation of platooning trucks

On-track validation of CAV controls (**EEMS082**)

Other EEMS projects:

- **EEMS086** => RoadRunner commercialization + human driver validation
- ANL Core Tools—Simulation (**EEMS013**) => Autonomie and AMBER
- ANL Core Tools—Hardware (**EEMS041**) => data for CAV model validation
- SMART Tools and Process Development (**EEMS058**)

Remaining Challenges and Barriers Post Project

- **Limited number of routes & scenarios**
  - Many routes (44), but high variance in results suggest more are needed
  - Sample not designed to be **statistically representative** of US “driving mix” (urban vs rural, highway vs. arterial, etc.)
  - **Traffic** not considered in this study
- **True optimality is hard to achieve**, because of:
  - Partial knowledge of the future
  - Calibration of controller parameters, not optimized in this project
  - Modeling errors in the models used for optimization
- **Implementation**
  - Controls designed to be “real-world implementable,” but no validation yet.
  - Trade-offs between energy consumption, drivability, and travel time require further research.

Proposed Future Research Beyond this Project

- **Continue RoadRunner + CAV/human driver model development**
  - Better models thanks to driving data from OEMs + testing (EEMS086)
  - Maturation of RoadRunner and public release (EEMS086)
- Improve **eco-driving controls** to work for more vehicles, leverage various levels of automation and connectivity, and be smarter with AI
- **Run larger, more representative case studies**, incl. with traffic
- **Deploy and validate controls** in real vehicles, in lab (vehicle-in-the-loop EEMS041) or on track settings (EEMS082)

Any proposed future work is subject to change based on funding levels

Summary

Developed RoadRunner and models

- RoadRunner = new simulation framework for developing energy-efficient CAVs
- Validated models of human driving, truck platooning, ACC

Developed CAV controls for energy-efficiency

- Developed real-world implementable CAV eco-driving controllers:
  - Optimization of powertrain AND speed
  - Multiple powertrains: conventional, EV, HEV

Evaluated energy impact of CAV controls

- Up to 22% energy savings for CAV in lead position w/ V2I
- Adding powertrain to the optimization saves up to extra 9% (pts)
- V2I brings up to 10% (pts) extra savings
- Non-CAVs also benefit (up to 8% savings) [following a CAV]

Future research*

- Better and more robust controls with AI, real-world demonstration and validation, larger more representative case studies (incl. traffic)

*Any proposed future work is subject to change based on funding levels

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SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Energy-Efficient Connected and Automated Vehicles

FOR MORE INFORMATION

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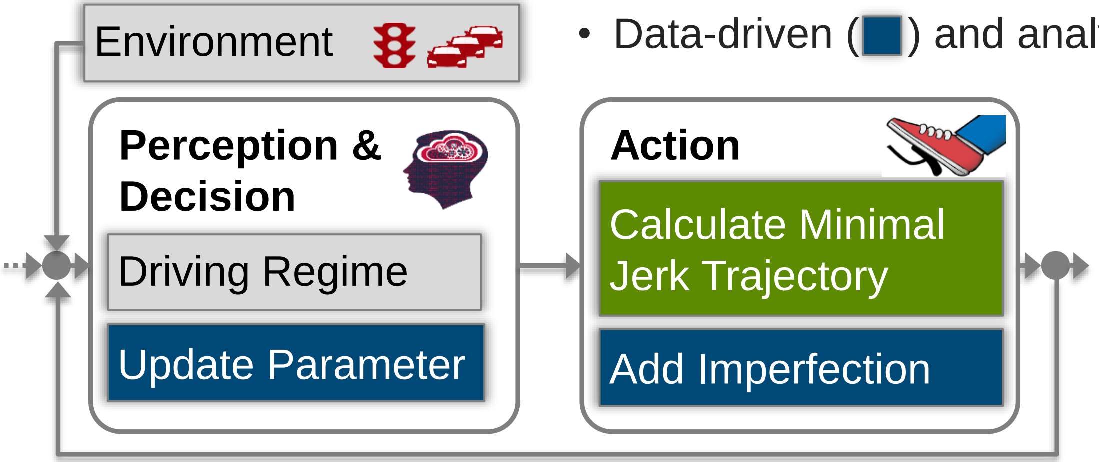
TECHNICAL BACKUP SLIDES

Developed a Human Driver Model



- Data-driven (■) and analytical approach (■)

Perception & Decision (P&D) model to capture the cognitive process of human brain

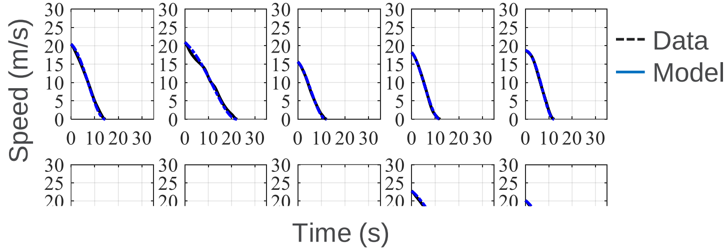
- *Determine driving regimes and their parameters*
- *e.g., determine the acceleration time and distance after a vehicle launches from a stop*

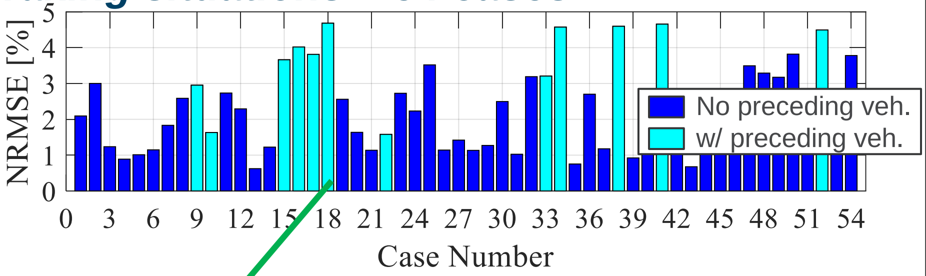
Action model to capture human driving behaviors impacting the state of the vehicle

- *Generate vehicle state trajectories*
- *e.g., using P&D parameters, compute vehicle state trajectories for an acceleration regime*

Validated Driver/Action Model over Small Real-World Data Sample

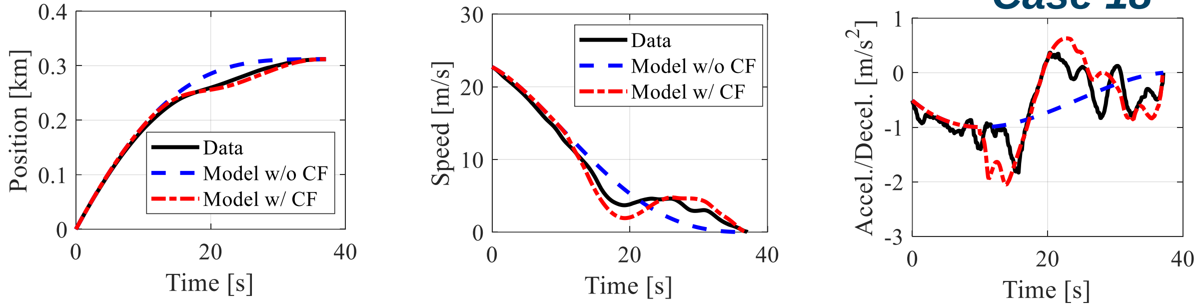
Comparing speed vs time for braking situations – 54 cases





*NRMSE = Normalized Root-Mean-Squared-Error

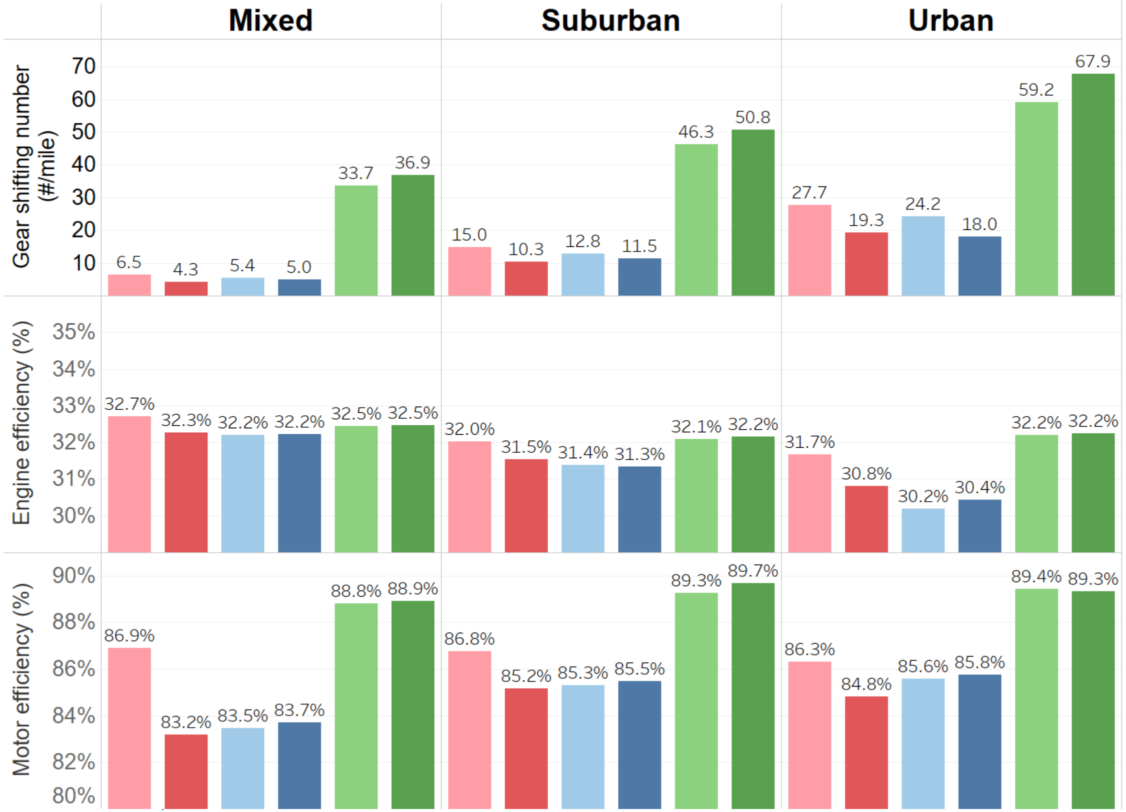
Case 18



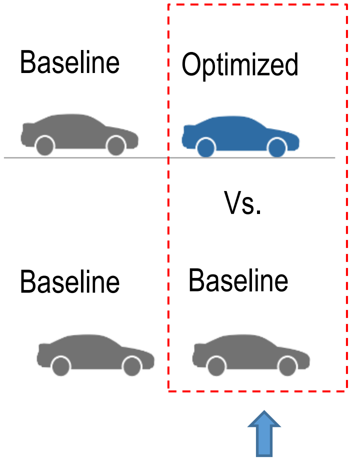
- Vehicle state trajectories (incl. acceleration) show good match (but small sample)
- Model capture car-following (CF) driving

Eco-Driving Affects Component Operations

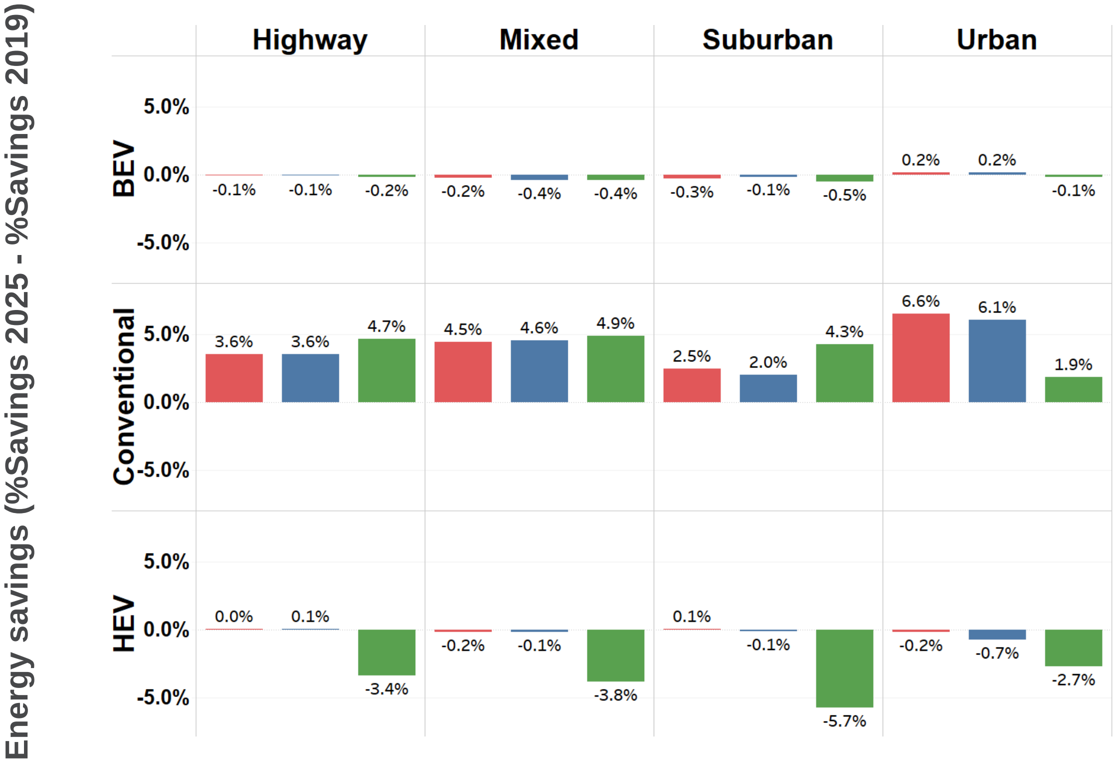
HEV, current tech.

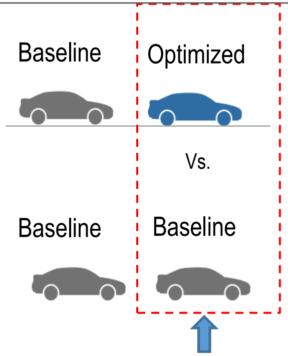


Control
- Baseline
- Baseline + V2I
- EcoDrv Spd/Accel
- EcoDrv Spd/Accel, V2I
- EcoDrv PT+Spd
- EcoDrv PT+Spd,V2I



Impact of VTO Technology: 2025 vs 2019 Savings





- *For conventional, greater savings of CAV controls in 2025 than in 2019, thanks to low-load engine efficiency improvements*
- *HEV, EV: same savings in 2025 and 2019*
- *Spd+PT for HEV savings go down because of improvements for the baseline case already improve powertrain efficiency*

Difference in percentage of energy consumption savings between a 2025 and a 2019 vehicle in lead position for various types of controllers. If positive (e.g. 10%), savings for CAV-2025 vs baseline-2025 are greater (e.g. by 10 percentage points) than savings for CAV-2019 vs baseline-2019

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